

# A DISSECTION OF FOREGROUNDS IN EPOCH OF REIONIZATION OBSERVATIONS FROM THE MURCHISON WIDEFIELD ARRAY

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## ABSTRACT

Detection of 21 cm emission of neutral hydrogen from the epoch of reionization, at redshifts  $z > 6$ , is limited primarily by foreground emission. We investigate the chromatic signatures of an all-sky foreground model imprinted by an instrumental transfer function. Using the delay spectrum technique **that maps the Fourier transform of the measurements to locations of foreground objects on the celestial sphere through delays in signals received by antenna pairs**, we demonstrate that the foreground signatures that have the largest impact on the HI signal arise from power received far away from the primary field of view. Comparing data from recent Murchison Widefield Array observations with simulations separated into components based on type of emission, we identify diffuse emission near the horizon as a significant contributing factor, even on wide antenna spacings **which are usually not sensitive to diffuse emission**. For signals entering through the primary field of view, compact emission dominates the foreground contamination. These two mechanisms imprint a characteristic *pitchfork* signature on the “foreground wedge” in Fourier space. Based on these results, we propose that selective down-weighting of data based on antenna spacing vector and time will mitigate foreground contamination substantially (up to a factor  $\sim 10$  with negligible loss of sensitivity) in redshifted 21 cm power spectrum analysis.

*Keywords:* cosmology: observations — large-scale structure of universe — methods: statistical — radio continuum: galaxies — reionization — techniques: interferometric

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## 1. INTRODUCTION

At the end of the recombination epoch, the Universe was completely neutral. This period, referred to as the *Dark Ages* in the Universe’s history, is characterized by the localized accumulation of matter under the influence of gravity. And it ended with the formation of the first stars and galaxies which started emitting ultra-violet and X-ray radiation, thereby reionizing the neutral medium in their surroundings. This commenced the epoch of reionization (EoR) — a period of non-linear growth of matter density perturbations and astrophysical evolution. Studying the EoR holds the key to understanding this evolution.

Observations of redshifted 21 cm radiation generated by the spin flip transition of HI has been identified as a direct probe of the EoR (Sunyaev & Zeldovich 1972; Scott & Rees 1990; Madau et al. 1997; Tozzi et al. 2000; Iliev et al. 2002). Detecting this signal has recently emerged as a very promising experiment to fill the gaps in our understanding of the Universe’s history.

Sensitive instruments such as the Square Kilometre Array (SKA) are required for direct observation and tomography of redshifted HI. Numerous **pathfinders and precursors** to the SKA such as the Murchison Widefield Array (MWA; Lonsdale et al. 2009; Tingay et al. 2013; Bowman et al. 2013), the Low Frequency Array (LOFAR; van Haarlem et al. 2013), and the Precision Array for Probing the Epoch of Reionization (PAPER; Parsons et al. 2010) have become operational with enough sensitivity for a statistical detection of the EoR HI power spectrum (Bowman et al. 2006; Parsons et al. 2012a; Beardsley et al. 2013; Dillon et al. 2013; Thyagarajan et al. 2013; Pober et al. 2014). **The Hydrogen Epoch of Reionization Array<sup>22</sup> (HERA) is currently under construction using new insights gained with the MWA and PAPER.**

A key challenge in the statistical detection of the redshifted HI 21 cm signal, via the spatial power spectrum of temperature fluctuations, arises from the contamination by Galactic and extragalactic foregrounds (see, e.g., Di Matteo et al. 2002; Zaldarriaga et al. 2004; Furlanetto et al. 2006; Ali et al. 2008; Bernardi et al. 2009, 2010; Ghosh et al. 2012). Morales & Hewitt (2004) show that the inherent isotropy and symmetry of the EoR signal in frequency and spatial wavenumber ( $k$ ) space make it distinguishable from sources of contamination which are isolated to certain  $k$  modes by virtue of their inherent spectral smoothness (Morales et al. 2006; Bowman et al. 2009; Liu & Tegmark 2011; Parsons et al. 2012b; Dillon et al. 2013; Pober et al. 2013). **Since this contamination is expected to be several orders of magnitude stronger than the underlying EoR HI signal, it is critical to characterize foregrounds precisely in order to reduce their impact on EoR HI power spectrum detection sensitivity.**

Considerable effort has been and continues to be made towards understanding the  $k$ -space behavior of foreground signatures in the observed power spectrum and formulating robust estimators of the true power spectrum (Bowman et al. 2009; Liu et al. 2009; Datta et al. 2010; Liu & Tegmark 2011; Morales et al. 2012; Trott et al.

2012; Pober et al. 2013; Thyagarajan et al. 2013; Dillon et al. 2014; Liu et al. 2014a,b). **A model that provides a generic explanation for the observed foreground power spectrum has emerged, whereby the wide-field (and chromatic) response of the instrument causes the power in smooth spectrum foregrounds to occupy higher  $k$ -modes into the so-called ‘wedge’.** The conservative foreground strategy that has developed alongside this work is to discard  $k$ -modes which could be contaminated (*avoidance*). The more aggressive alternative is to subtract a sky model and regain access to modes discarded by *avoidance*. In both cases, which parts of the sky are most critical to either *avoid* or *subtract* has remained largely uncertain. Here, we will focus primarily on extending the *avoidance* strategy by identifying foreground components at greatest risk to “leak” from foreground modes to EoR modes and demonstrating a scheme for down-weighting these components.

Foregrounds with intrinsic deviations from spectral smoothness, instruments with high chromaticity, polarization leakage, calibration errors, or approximations in power spectrum analyses can contaminate the true EoR HI power spectrum. Here we use existing catalogs and a high fidelity instrumental model to capture both foreground and instrumental chromaticity. To decouple these effects from possible analysis effects, such as those pointed out by Hazelton et al. (2013), we compute power spectra using a ***Per-Baseline*** approach of Parsons et al. (2012b). This approximates the power spectrum as the inverse Fourier transform of the spectra generated by the instrument’s correlator.

After matching real observations from the Murchison Widefield Array with instrumental simulations of the entire known sky, we examine the **shape of the delay spectrum** of each baseline. We report two important findings: the foregrounds that most severely **obscure** the redshifted 21 cm power spectrum are not caused by emission in the central field of view, but rather by bright objects from near the horizon; and, diffuse Galactic emission plays a significant role hitherto unpredicted. We quantify this contamination by separating the simulations into components based on type of foreground emission. We then arrive at a new method for minimizing the contribution of bright foregrounds which uses prior knowledge of the sky to down-weight adversely contaminated baselines.

In §2 we **provide a brief overview of the delay spectrum technique** (Parsons et al. 2012a,b). In §3, we describe the MWA setup, summarize the observing parameters, and present the resulting data. Simulations using these observing parameters are described in §4 and analyzed by sky location and type of emission in §5. In §6, we offer an initial description of a more precise foreground avoidance technique. We present a summary of our work and findings in §8.

## 2. DELAY SPECTRUM

Interferometer array data known as *visibilities*,  $V_{bf} \equiv V_{bf}(\mathbf{b}, f)$ , represent correlations between time-series of electric fields measured by different antenna pairs with separation vectors  $\mathbf{b}$  and then Fourier transformed along the time axis to obtain a spectrum along the frequency ( $f$ ) axis. If  $I(\hat{\mathbf{s}}, f)$  and  $A(\hat{\mathbf{s}}, f)$  are the sky brightness and

<sup>22</sup> <http://reionization.org/>

antenna's directional power-pattern, respectively, at different frequencies as a function of direction on the sky denoted by the unit vector ( $\hat{s}$ ), and  $W_f \equiv W_f(f)$  denotes instrumental bandpass weights, then  $V_{bf}$  can be written as (with a slight adaptation from van Cittert (1934), Zernike (1938), and Thompson et al. (2001)):

$$V_{bf} = \iint_{\text{sky}} A(\hat{s}, f) I(\hat{s}, f) W_f e^{-i2\pi f \frac{\mathbf{b} \cdot \hat{s}}{c}} d\Omega, \quad (1)$$

where,  $c$  is the speed of light, and  $d\Omega$  is the solid angle element to which  $\hat{s}$  is the unit normal vector. We wish to **note** that this equation is valid **even for wide-field applications where the sky cannot be approximated to be flat**.

The *delay spectrum*,  $V_{b\tau} \equiv V_{b\tau}(\mathbf{b}, \tau)$ , is defined as the inverse Fourier transform of  $V_{bf}$  along the frequency coordinate:

$$V_{b\tau} \equiv \int V_{bf} W'_f e^{i2\pi f \tau} df, \quad (2)$$

where,  $W'_f \equiv W'_f(f)$  is a spectral weighting function which can be chosen to control the quality of the delay spectrum (Thyagarajan et al. 2013; Vedantham et al. 2012), and  $\tau$  represents the signal delay between antenna pairs:

$$\tau = \frac{\mathbf{b} \cdot \hat{s}}{c}. \quad (3)$$

$V_{b\tau}$  is expressed in observer's units as Jy Hz.

### 2.1. Resemblance to Spatial Power Spectrum

Equation 1 can be **equivalently re-expressed** as:

$$\begin{aligned} V_{uf} &\equiv V_{uf}(\mathbf{u}, f) \\ &= \iint_{\text{sky}} A(\hat{s}, f) I(\hat{s}, f) W_f e^{-i2\pi \mathbf{u} \cdot \hat{s}} d\Omega, \end{aligned} \quad (4)$$

where,  $\hat{s}$  is measured with reference to a location on the sky referred to as the *phase center*, and  $\mathbf{u} \equiv (u, v, w)$  denotes the spatial frequency vector.  $w$  is aligned parallel to the direction of the phase center, while  $u$  and  $v$  lie on the transverse plane perpendicular to it. For measurements that are constrained to lie on this plane, we can choose  $w = 0$  without loss of generality and  $\mathbf{u}$  effectively reduces to  $\mathbf{u} \equiv (u, v)$ , a two-dimensional vector. Then,  $\mathbf{u}$  is directly related to the transverse spatial wavenumber mode as:

$$\mathbf{k}_\perp \equiv \frac{2\pi \mathbf{u}}{D}, \quad (5)$$

where,  $D \equiv D(z)$  is the transverse comoving distance at redshift  $z$ .

Since we are concerned with a redshifted HI spectral line from cosmological distances,  $f$  is a measure of cosmological distance along the line of sight.  $\eta$ , which is the Fourier transform dual of  $f$ , is used to denote the spatial frequency along the line of sight and has units of time. It is directly related to the line-of-sight wavenumber,

$$k_\parallel \approx \frac{2\pi \eta f_{21} H_0 E(z)}{c(1+z)^2}, \quad (6)$$

where,  $f_{21}$  is the rest frame frequency of the 21 cm spin flip transition of HI, and  $H_0$  and  $E(z) \equiv [\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda]^{1/2}$  are standard terms in cosmology. This approximation holds under the assumption that the redshift range (or frequency band) is small enough within which cosmological evolution is negligible. Thus,

$$\begin{aligned} V_{u\eta} &\equiv V_{u\eta}(\mathbf{u}, \eta) \\ &\equiv \int V_{uf}(\mathbf{u}, f) W'_f e^{i2\pi f \eta} df \end{aligned} \quad (7)$$

represents the true spatial Fourier representation of the three-dimensional sky brightness distribution. This approach has been discussed in detail in Morales & Hewitt (2004). The spatial power spectrum of EoR HI distribution,  $P(\mathbf{k}_\perp, k_\parallel)$ , and  $V_{u\eta}$  are related by (Morales & Hewitt 2004; McQuinn et al. 2006; Parsons et al. 2012a):

$$P(\mathbf{k}_\perp, k_\parallel) \simeq |V_{u\eta}|^2 \left( \frac{A_e}{\lambda^2 \Delta B} \right) \left( \frac{D^2 \Delta D}{\Delta B} \right) \left( \frac{\lambda^2}{2k_B} \right)^2, \quad (8)$$

where,  $A_e$  is the effective area of the antenna,  $\Delta B$  is the bandwidth,  $\lambda$  is the wavelength of the band center, and  $k_B$  is the Boltzmann constant. Thus,  $V_{u\eta}$  inferred from observations, also in units of Jy Hz, can be converted into an equivalent cosmological HI power spectrum  $P(\mathbf{k}_\perp, k_\parallel)$ , in units of  $\text{K}^2 \text{Mpc}^3$ .

Without loss of generality, the phase center can be assumed to be the zenith relative to the local tangent plane. Then  $\mathbf{u}$  lies on this plane for measurements constrained to be on it. If the array of antennas are also coplanar lying on the local tangent plane, then  $\mathbf{u} = \mathbf{b}/\lambda$ . Under such circumstances, equations 1 and 3 closely resemble equations 4 and 7 respectively. However, they are not quite identical to each other. The difference basically arises from the fact noted above that  $\mathbf{b}$  is independent of frequency while  $\mathbf{u}$  is not. Parsons et al. (2012b) and Liu et al. (2014a) have discussed the mathematical correspondence between the two.

Foregrounds can be described in both the delay spectrum and Fourier frameworks. For our study, which primarily concerns with foreground characterization, we find the former to be simple and yet extremely useful, while maintaining a close correspondence with the latter despite subtle differences. In order to express a quantity derived from  $V_{u\eta}$  that has units identical to that of aforementioned cosmological HI power spectrum derived, we define:

$$P_d(\mathbf{k}_\perp, k_\parallel) \equiv |V_{b\tau}|^2 \left( \frac{A_e}{\lambda^2 \Delta B} \right) \left( \frac{D^2 \Delta D}{\Delta B} \right) \left( \frac{\lambda^2}{2k_B} \right)^2, \quad (9)$$

where,  $\mathbf{u}$  and  $\eta$  in equations 5 and 6 have been correspondingly replaced with  $\mathbf{b}/\lambda$  and  $\tau$  respectively.

In summary, the delay spectrum,  $V_{b\tau}$ , is obtained from *visibilities* which are the basic data blocks measured by each antenna pair, using equations 1 and 2.  $V_{b\tau}$  captures all the effects of EoR HI signal corruption caused by foregrounds and the instrument. At the same time, it is closely related to the sought power spectrum  $P(\mathbf{k}_\perp, k_\parallel)$  containing critical information about spatial scales. For purposes of illustration later in this paper, we often use the quantities  $|V_{b\tau}|$  and  $P_d(\mathbf{k}_\perp, k_\parallel)$ .

Note that since *visibility* is a complex quantity, its **delay transform contains** positive and negative delays.

Negative and positive delays correspond to the two hemispheres of the sky as transected by the antenna spacing vector. In this paper,  $\mathbf{b}$  is assumed to be on a coordinate system aligned with the local east, north (along local meridian) and upward (zenith) directions at the telescope site. Hence, a perfectly eastward oriented antenna spacing will observe objects in the eastern and the western skies at positive and negative delays, respectively. Similarly, an object in the northern sky will appear at a positive delay at an antenna spacing oriented northward. For all observations used in this study, we use the zenith as the phase center.

We give a brief overview of some parameters of Fourier space which is generic to all experiments that use a similar approach. Figure 1 illustrates the Fourier space, specific to the MWA, in which the delay (and power) spectra of HI from the EoR are presented in this paper.  $|\mathbf{b}|$  and  $k_{\perp}$ , denoting spatial scales in the transverse direction (**tangent plane to the celestial sphere**), form the  $x$ -axis.  $\tau \approx \eta \propto k_{\parallel}$ , denoting spatial scales along line-of-sight form the  $y$ -axis. Foreground emission maps to a wedge-shaped region in Fourier space, hereafter referred to as the *foreground wedge* (Datta et al. 2010), whose boundaries are determined by the antenna spacings and the light travel times across them. These boundaries, called horizon delay limits (Vedantham et al. 2012; Parsons et al. 2012b), are shown by solid lines. The spectral transfer function of the instrument convolves the *foreground wedge* and stretches it further (unshaded narrow strips bounded by solid and dashed lines) along  $\tau$ -axis (Parsons et al. 2012b; Thyagarajan et al. 2013). The width of this narrow strip is inversely proportional to the operating bandwidth. The region of Fourier space excluding the *foreground wedge* and the narrow strips is the so-called *EoR window*, shown in light and medium shades. However, the instrument used in our study, namely the MWA, has a passband constructed using coarse channels with a characteristic shape giving rise to periodic gratings thereby resulting in repetitions of the *foreground wedge* at multiples of  $0.78 \mu\text{s}$ .

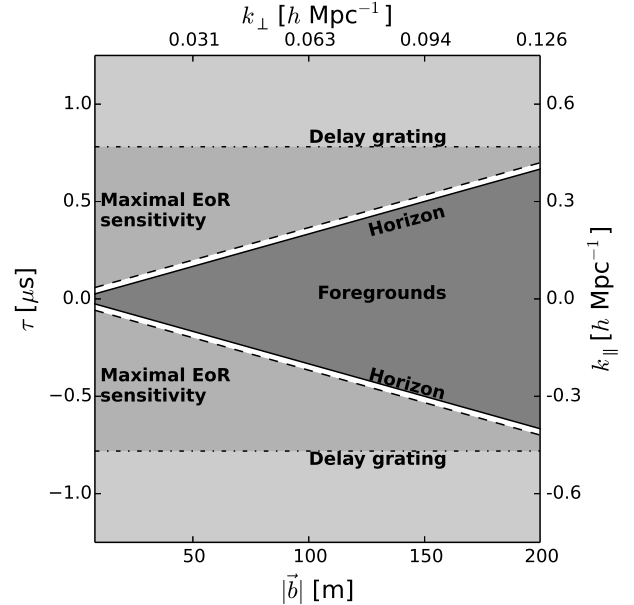
In the context of EoR studies in Fourier space, the HI power spectrum from the EoR is expected to decrease rapidly with  $|\mathbf{k}|$ . Hence, the brightest EoR signal will be observed on the shortest baselines and smallest delays. Thus the region of interest for EoR studies is slightly beyond the horizon delay limits (dashed lines) and inside the first grating on either side ( $|\tau| \lesssim 0.78 \mu\text{s}$ , dot-dashed lines) caused by the instrument's spectral transfer function. We call this region with medium shade as the *EoR window* in this paper. The MWA EoR collaboration actively uses this as a test region in Fourier space for diagnostics on data quality.

For geometrical intuition, we restrict the orientation ( $\theta_b$ , measured anti-clockwise from East) of all baselines to lie in the range  $-67.5^\circ \leq \theta_b < 112.5^\circ$ . Baselines oriented in the other half-plane measure conjugate visibilities with delays of equal magnitude but of opposite sign and hence are ignored in our analysis.

### 3. EXAMPLE DATA

#### 3.1. The Murchison Widefield Array (MWA)

MWA construction was completed in 2012 and, after commissioning, began its EoR observing program in



**Figure 1.** Fourier space in which delay (and power) spectra of EoR HI signals are presented. The  $x$ -axis is denoted by  $|\mathbf{b}|$  (antenna spacing) or  $k_{\perp}$  (transverse wavenumber). The  $y$ -axis denoted by  $\tau$  (delay) or  $k_{\parallel}$  (line-of-sight wavenumber). Here,  $k_{\perp}$  and  $k_{\parallel}$  are obtained for a frequency of 185 MHz. The dark shaded region is referred to as the *foreground wedge* where smooth spectrum foregrounds reside. Its boundaries (solid lines), given by light travel time for corresponding antenna spacings, are referred to as horizon delay limits. Regions excluding the *wedge* and narrow extensions of the *wedge* (white unshaded strips) caused by convolution with the instrument's spectral transfer function are expected to be relatively free of foreground contamination. Due to an undesirable grating pattern (dot-dashed lines) of the instrument used in this study, namely the MWA, we conservatively identify a restricted region of high EoR sensitivity (medium shade) and refer to it as the *EoR window* in this paper.

2013. In its final configuration the MWA is a 128-tile interferometer array capable of observing a 30.72 MHz instantaneous band anywhere in the range 80–300 MHz. Each tile is a phased array of 16 dipoles, each in the shape of a bow-tie. This yields a primary field of view  $\gtrsim 20^\circ$  wide and multiple secondary lobes. The array is arranged as a centrally condensed core of  $\sim 300$  m — there are many spacings in the range 5–50 m — and a radial density that falls off as the inverse of the radius, with the longest baselines at 3 km (Beardsley et al. 2012). Here we focus on antenna spacings  $|\mathbf{b}| \leq 200$  m (spatial scales relevant to reionization) and a frequency range 170–200 MHz. The center frequency of 185 MHz corresponds to a redshift,  $z \simeq 6.68$ . **At this frequency, we use  $A_e = 10.5 \text{ m}^2$ .**

The MWA passband of width  $\Delta B = 30.72$  MHz is divided coarsely into  $24 \times 1.28$  MHz sub-bands with each sub-band weighted by a digital filter. The coarse channel shape is obtained using a 8-tap polyphase filter bank (PFB) and a Kaiser window with parameter  $\beta = 5$ . **Each of these coarse bands consists of 32 fine channels of width 40 kHz each.** After correcting for the shape of these coarse channels, the fine channels at the edges of these sub-bands are flagged because they are known to be contaminated by aliasing at a low level. Any spectral flags, or other known weights constitutes

$W_f$  in equation 1.

### 3.2. Observation Parameters

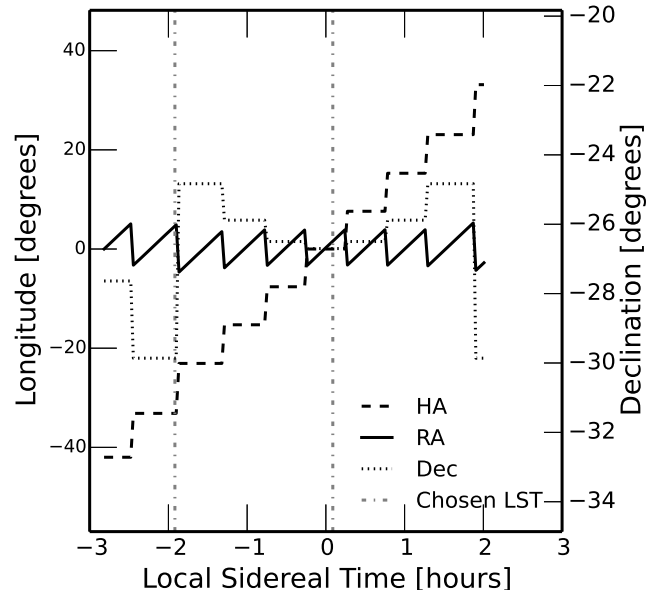
The MWA targets two primary low-foreground fields for reionization observations. Here, we focus on the field at  $RA = 0^h$ ,  $Dec = -30^\circ$ . The MWA tracks a patch of sky through antenna beams formed and steered electronically by controlling delay settings of the dipoles in an MWA tile. The pointing system is capable of steering to points on a regular  $\sim 7^\circ$  grid. During observations we allow the sky to drift across the nearest available pointing, shifting between grid points as necessary (once in  $\sim 30$  minutes). This process is repeated throughout the course of the observation  $\approx 4.86$  hours. Figure 2 illustrates how the apparent pointing oscillates around the desired pointing direction.

The observations shown here were undertaken on 2013 August 23. We have chosen two, 112 second long sections from this night for detailed study. These were chosen to provide a selection of possible foreground and instrumental conditions. As an example of a nominal observing setup we choose a zenith pointing; as an example of poor foreground conditions, we choose a pointing when the field is  $\sim 2$  hours from zenith. This pointing has a significantly higher secondary lobe structure and is observed when the bright galactic center is well above the horizon.

The *local sidereal time* (LST) at these two snapshots are shown in Figure 2 as vertical lines at **22.08 hours** (**-1.92 hours in the figure**) and 0.09 hours which are hereafter denoted as *off-zenith* and *zenith* pointings, respectively.

### 3.3. Initial Data Processing

The data are flagged<sup>23</sup> for interference (Offringa et al. 2010, 2012), removing 3% of the data and averaged in time and frequency from the raw 0.5 s, 40 kHz to 2s, 80 kHz. These data are then calibrated to a simulation of the sky containing 2420 point-like objects selected from the MWA Commissioning Survey (MWACS; Hurley-Walker et al. 2014). It has a flux density limit of 25 mJy and a declination range of  $-12^\circ$  to  $-40^\circ$  evenly covering the field of view of the observations reported here. The objects used in calibration are selected to lie inside the 5% contour of the primary lobe of the tile power-pattern. The calibration algorithm – based on forward modeling software by Sullivan et al. (2012) and the calibration method described by Salvini & Wijnholds (2014) – computes complex gain solutions per channel per antenna averaged to two minute intervals. The solutions are fairly low signal-to-noise so we iteratively average along the antenna and frequency dimensions to capture the relatively independent passband and antenna-to-antenna variation. First, we average the channel gains over all antennas to obtain a high signal-to-noise measurement of the bandpass. After applying this single passband, we do a second round of calibration and fit second and first order polynomials for amplitude and phase respectively for each antenna. This flattens any residual variation in bandpass and removes small phase slopes due to variations in cable delay. Finally, we fit for an



**Figure 2.** MWA tile beam pointing directions during the course of the observation. The  $x$ -axis refers to the *local sidereal time* (LST). The axis on the left refers to longitudes, namely, Right Ascension (RA) and Hour Angle (HA). Negative values of RA, HA, and LST are to be interpreted as having been wrapped around by  $360^\circ$  or 24 hours. The axis on the right refers to the declination of the pointing direction. The RA, HA, and declination are plotted with solid, dashed and dotted lines respectively. The sky is allowed to drift for  $\sim 30$  mins before the beamformer delay settings change in a discrete step to center the beam around  $RA = 0^h$ ,  $Dec = -30^\circ$ . Dot-dashed vertical lines show the LST of *off-zenith* and *zenith* pointings used in our study.

additional phase known to be caused by small reflections in subset of cables.

### 3.4. Deconvolved Delay Spectrum

We obtain the delay spectrum of these calibrated visibilities by taking the delay transform of each baseline's spectrum (equation 2) choosing  $W'_f$  to be a *Blackman-Harris* window function. The spectrum is multiplied by the additional weight of the flagged channels which occur rarely for interference and regularly every 1.28 MHz where the edges of coarse channels are known to have a small aliasing effect. In delay-space, these weights translate into a convolution by a grating point spread function (PSF) with gratings at multiples of  $\tau = 0.78 \mu s$ . We deconvolve this PSF using a one dimensional CLEAN algorithm (Taylor et al. 1999) as described for the delay axis by Parsons & Backer (2009); Parsons et al. (2012b). The CLEAN procedure iteratively finds and subtracts peak values convolved by the Fourier transform of the weights. We limit the selection of peaks to modes inside the horizon delay limit, corresponding to smooth spectrum objects in the visible sky hemisphere.

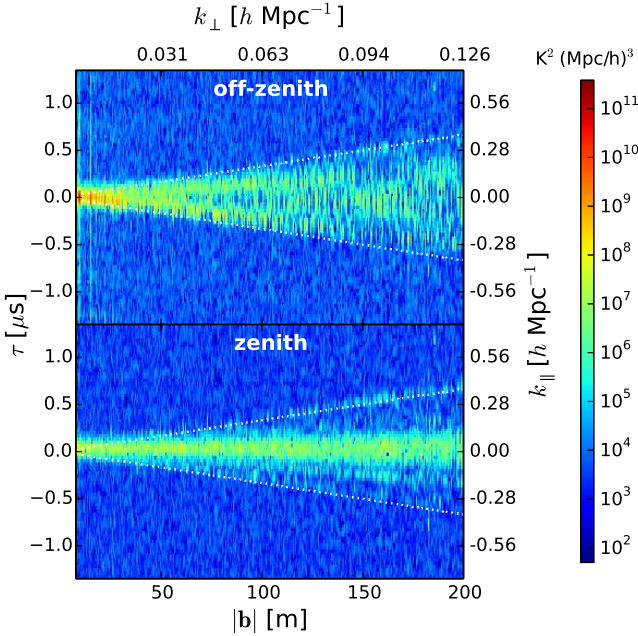
In subsequent sections, we plot the amplitude of the delay spectrum,  $|V_{b\tau}|$ , sorted by baseline length,  $|\mathbf{b}|$ . Note that visibilities from different baselines have not been averaged together in this analysis.

We show results of delay spectrum from MWA data after deconvolution along the delay axis in Figure 3. The principle feature is the *foreground wedge*, whose bound-

<sup>23</sup> <http://sourceforge.net/p/aoflagger>

aries, marked by white lines, increase linearly with light travel time corresponding to baseline length. Note that the wedge is not filled out uniformly. Each baseline has a different orientation and resulting response to different objects in the sky. It is this variation that we will explore below.

The *off-zenith* pointing has notably higher power in the foreground wedge than in the *zenith* pointing. This is shown later in §5.1 to be due to response of the array to the bright Galactic center and Galactic plane in the westward sky. Consequently, the contamination into the *EoR window* is also higher, especially on short antenna spacings. Emission in the *zenith* pointing is more centrally concentrated due to a *zenith-centered power-pattern* and faster suppression of response away from zenith, whereas the *off-zenith* pointing has a *power-pattern phased eastward of zenith* and is also more responsive to emission farther away from the primary lobe relative to that in the *zenith* pointing. The power pattern is discussed in detail in §4.1 and Figure 4.



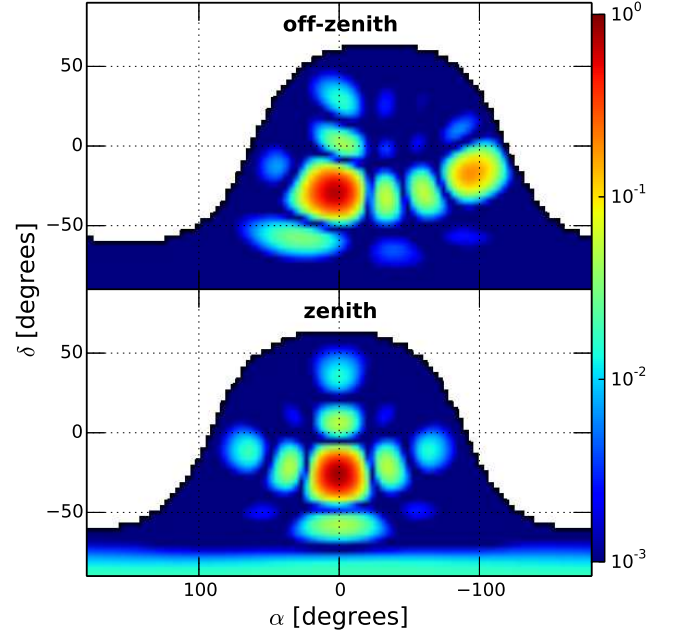
**Figure 3.** Delay spectra power of two observations of the EoR field ( $\text{RA} = 0^{\text{h}}$ ,  $\text{Dec} = -30^{\circ}$ ) at an *off-zenith* pointing (top) when tiles have significant secondary lobes in the direction of the Galactic center and a *zenith* pointing (bottom) where secondary lobes are minimal and the Galaxy has set. **In both cases, the delay spectra are phased to the zenith and thus the foreground wedge boundaries are symmetric around  $\tau = 0$ .** For reference, the  $k$ -space equivalent of  $\tau$  and  $|b|$ , namely,  $k_{\parallel}$  and  $k_{\perp}$  are shown at the axes on the right and top respectively. White lines mark the boundaries of foreground wedge determined by light travel time across each baseline. Smooth spectrum objects predominantly reside in this foreground wedge. The logarithmic color scale (shown at the right) is common to both panels.

#### 4. SIMULATIONS

We describe the instrumental and foreground models we use in our simulations.

##### 4.1. Instrument Model

The instrument model consists primarily of the tile beam power-pattern,  $A(\hat{s}, f)$  (see equation 1). It is modeled as a mutually-coupled 4-by-4 dipole array with the overall power-pattern of each individual dipole calculated via finite element electromagnetic simulation (Sutinjo et al. 2014). To speed up simulations, we find that a phased array of isotropic radiators at a height of 0.3 m above an infinite ground plane provides a very good approximation to the full simulation, hence we use the idealized dipoles. We also assume that each individual dipole signal has random delay fluctuations of rms 0.05 ns, a number in line with the known repeatability and stability level of the analog signal chain (Bowman et al. 2007). Besides having the effect of adding a time-dependent uncertainty in the power pattern, these random delay fluctuations reduce the coherence in the phased addition of dipole signals resulting in deviations from predicted models of the power-pattern, most prominently at its nulls. The power-patterns so obtained are shown in Figure 4 for the pointings chosen in our study.



**Figure 4.** Models of MWA tile power-pattern for *off-zenith* (top) and *zenith* pointings (bottom) at 185 MHz. An MWA tile is modeled as a 4×4 array of isotropic radiators placed 0.3 m above an infinite ground plane. Random fluctuations of rms 0.05 ns have been added to delay corrections during the phased addition of voltages from these isotropic radiators. The logarithmic color scale (shown on the right) is common to both panels.

Estimation of  $T_{\text{sys}}$  from MWA data is a subject of active investigation. For our work, we estimate thermal noise in the data using the *rms* of  $V_{b\tau}$  obtained after *delay-deconvolution* across all antenna spacings for  $|\tau| \geq 1 \mu\text{s}$  using the relations:

$$\Delta V_{b\tau}^{\text{rms}} = \sqrt{N_{\text{ch}}} \Delta V_{bf}^{\text{rms}} \Delta f, \text{ and} \quad (10)$$

$$\Delta V_{bf}^{\text{rms}} = \frac{2 k_B T_{\text{sys}}}{A_e \sqrt{2 \Delta f \Delta t}}, \quad (11)$$

where,  $\Delta f = 80 \text{ kHz}$ ,  $\Delta t = 112 \text{ s}$ , and  $N_{\text{ch}} = \Delta B / \Delta f$  is the number of frequency channels. The choice



of threshold for  $\tau$  is well outside the *foreground window*, where foreground contamination is negligible and thus makes a robust estimation of  $T_{\text{sys}}$  possible. We find the average system temperature to be  $\sim 95$  K across all frequency channels and across all antenna pairs throughout the course of the observation. Hence, for our simulations, we use  $T_{\text{sys}} = 95$  K to match the thermal noise observed in the data.

#### 4.2. Foreground Model

The MWA has a very wide field of view ( $\gtrsim 20^\circ$  at 185 MHz) and has non-negligible response all the way to the horizon. As already noted, foreground objects fill the *foreground wedge* with an amplitude which depends on the tile power gain in that direction, with objects at the horizon being closest to the boundaries of the *wedge*.

The degree to which these objects leak power into the spectral line-of-sight modes in the *EoR window* will be shown to depend primarily on the brightness of foregrounds near the boundaries of the *foreground wedge*. Thus, it is important to consider an all-sky model for foreground objects in evaluating the features seen in the power spectrum instead of restricting only to the primary field of view, a point also supported by Pober et al. (2015, in preparation).

We use an all-sky foreground emission model that includes both diffuse and bright compact components.

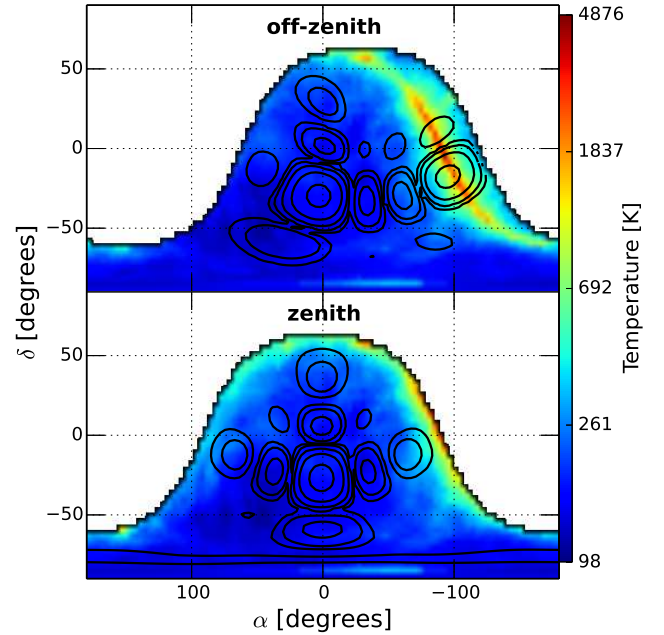
##### 4.2.1. Diffuse Foreground Model

For the diffuse component, we use an all-sky radio foreground model (de Oliveira-Costa et al. 2008) to estimate the emission at 185 MHz. At this frequency, since this map is predominantly based on the 408 MHz map of Haslam et al. (1982) which has an angular resolution of  $0.85^\circ$ , we smoothed the 185 MHz map to the same resolution. However, to avoid any artifacts from sampling this map, we sample it at  $\approx 27'$  intervals. We model the diffuse foreground spectra with a single spectral index at each pixel in the map, found by comparing model maps at 170 MHz and 200 MHz.

A low resolution version of the diffuse foreground model used is shown in Figure 5. Contours of the MWA tile power-pattern shown in Figure 4 are also overlaid. Of notable significance in the *off-zenith* pointing is the presence of a portion of the Galactic plane and the bright Galactic center in the westward sky, where the MWA tile power gain is significant ( $\gtrsim 12\%$ ). In the *zenith* pointing, the Galactic plane has set and the power-pattern in that direction is at least 16 times smaller.

##### 4.2.2. Compact Foreground Model

The model described in the preceding section is primarily a model of the diffuse foreground sky. While it contains faint compact emission blended in with the diffuse emission, **bright point sources have been removed** (de Oliveira-Costa et al. 2008). In order to supplement it with missing bright compact emission, we use classical radio source confusion estimates to determine the nominal flux density threshold and include point sources brighter than this threshold. It may be noted that slightly different criteria are in common use in radio astronomy to estimate radio source confusion



**Figure 5.** Sky brightness temperature of the diffuse foreground model at 185 MHz visible during *off-zenith* (top) and *zenith* (bottom) pointings. The color scale on the right is logarithmic and is common to both panels. Contours of power-pattern shown in Figure 4 are overlaid. The contour levels shown are 0.00195, 0.00781, 0.0312, 0.125, and 0.5. The Galactic center and a portion of the Galactic plane are prominently visible during the *off-zenith* pointing and the MWA tile power gain is significant ( $\gtrsim 12\%$ ) in that direction. In contrast, emission from the Galactic plane in *zenith* pointing is significantly lesser.

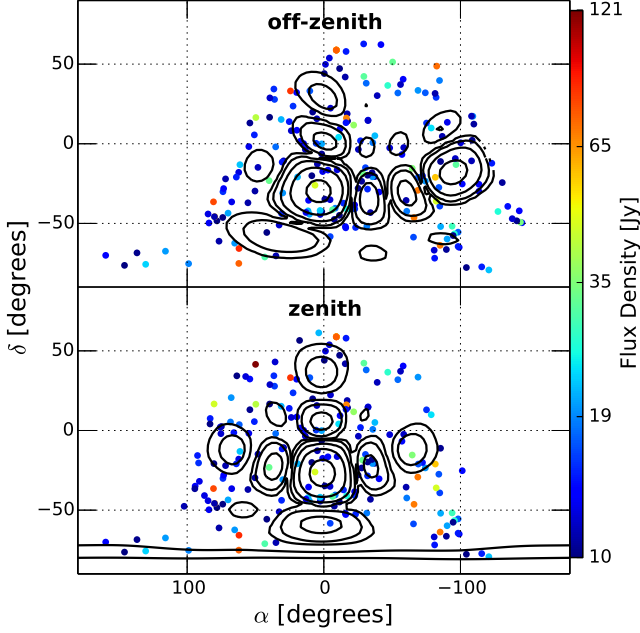
(see Appendix of Thyagarajan et al. 2013, and references therein). For an angular resolution of  $0.85^\circ$ , using a conservative ‘ $S_c = 5\sigma_c$ ’ criterion, we determine the flux density threshold to be  $\approx 10$  Jy. Other liberal criteria that yield a lower threshold carry a greater risk of double-counting point sources which might be already blended in with the diffuse sky model.

We use a combination of the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) at 1.4 GHz and the Sydney University Molonglo Sky Survey (SUMSS; Bock et al. 1999; Mauch et al. 2003) at 843 MHz to provide our point source catalog due to their complementary survey footprints covering the entire sky, and matched flux density sensitivity and angular resolution. The SUMSS catalog covers the sky with declination  $\delta < -30^\circ$  with a limiting peak brightness of 6–10 mJy/beam and an angular resolution of  $\sim 45''$ . The NVSS covers the sky with  $\delta > -40^\circ$  with a similar angular resolution and a limiting flux density of  $\approx 2.5$  mJy for point sources.

From the SUMSS catalog, we select **objects** whose deconvolved major axes are equal to  $0''$ , **thereby strictly selecting point sources**. From the NVSS catalog, we excluded objects that overlap with those in the SUMSS survey footprint. Point sources from NVSS were selected if the convolved major axes were not greater than  $\approx 47''$ , which matches the angular resolution of the survey. Using a mean spectral index of  $\langle \alpha_{\text{sp}} \rangle = -0.83$  (flux density,  $S(f) \propto f^{\alpha_{\text{sp}}}$ ) obtained by Mauch et al. (2003) for both NVSS and SUMSS catalog objects, we calculate the corresponding flux densities at 185 MHz,  $S_{185}$ . From this subset, we choose point sources with  $S_{185} \geq 10$  Jy. The

selection of such bright point sources is not affected by minor differences in flux density sensitivity of the two surveys. We verified that our selection criteria ensure a similar areal density of objects in the two surveys.

Based on these criteria, we selected 100 objects from the SUMSS catalog and 250 objects from the NVSS catalog. Together with the diffuse foreground model, we obtain an all-sky foreground model consisting of both compact and diffuse emission. Figure 6 shows the compact foreground emission model used in our study whose with contours of the power pattern overlaid. The flux densities of the point sources are indicated by the color scale.



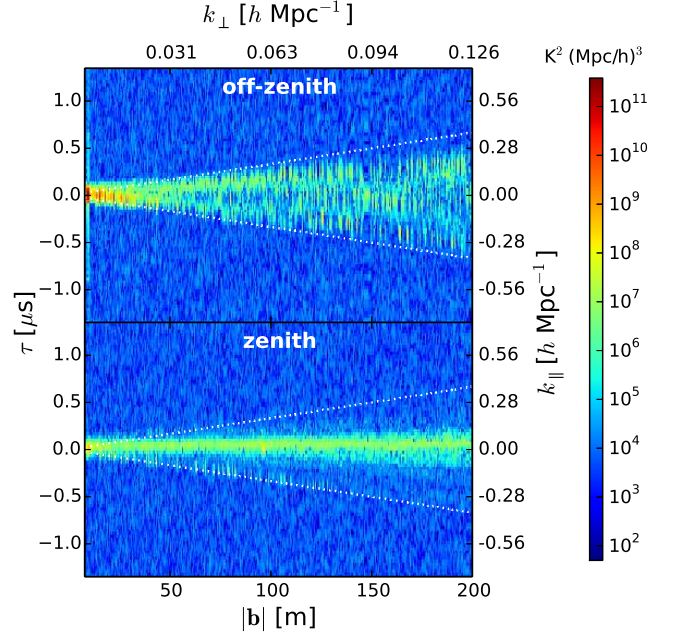
**Figure 6.** Flux densities of bright point sources at 185 MHz visible during *off-zenith* (top) and *zenith* (bottom) pointings. The color scale on the right is logarithmic and is common to both panels and corresponds to the color-coded filled circles. Contours of power-pattern shown in Figure 4 are overlaid. The contour levels shown are 0.001953125, 0.0078125, 0.03125, 0.125, and 0.5.

It is worth emphasizing that the ideal foreground model is one with an angular resolution finer than that of the instrument that covers the whole sky at the observing frequency, a point we will revisit later. For this study, we note that our conclusions are not significantly affected despite minor differences in the thresholds from different radio source confusion estimates.

#### 4.3. Comparison with Data

With the aforementioned foreground model, and instrumental and observational parameters, we simulate visibilities using equation 1. Figure 7 shows the amplitude of the delay spectrum from *off-zenith* and *zenith* pointings. Notice the qualitative agreement of amplitude and structure with those obtained from data shown in Figure 3. The Galactic center and the Galactic plane visible in the *off-zenith* pointing make it appear brighter in the *foreground wedge*.

In order to make a quantitative comparison of delay spectra obtained with MWA data and our simulations,



**Figure 7.** Same as Figure 3, but generated from simulated visibilities using the model described in §4. Note the similarity between the broad features to those in Figure 3.

we consider the uncertainty in the assumed spectral index of our foreground model. Our foreground models are derived from other higher frequency catalogs and sky maps. The inherent spread in spectral index increases the uncertainty while predicting fluxes at the observing frequency. Using simple error propagation, the fractional error in the delay spectrum **amplitude** caused by the spread in spectral index is  $\sim \ln(f_{\text{orig}}/f) \Delta\alpha_{\text{sp}}$ , where,  $f_{\text{orig}}$  is the original frequency at which the catalog or map was created,  $f = 185$  MHz is the MWA observing frequency, and  $\Delta\alpha_{\text{sp}}$  is the spread (HWHM) in spectral index. From Mauch et al. (2003), we assume  $\Delta\alpha_{\text{sp}} \approx 0.35$  for point sources from NVSS and SUMSS catalogs. Although the model of de Oliveira-Costa et al. (2008) yields a spectral index per direction on the sky, we could assume similar uncertainties exist in spectral indices of our diffuse sky model as well, which is predominantly derived from the 408 MHz map of Haslam et al. (1982). Thus, fractional errors in delay spectrum **amplitudes** from compact and diffuse components are  $\sim 70\%$  and  $\sim 30\%$  respectively.

In addition to intrinsic model uncertainty, delay spectra from simulations and data each have fluctuations due to thermal noise in the delay spectrum with rms  $\sim 1.4 \times 10^7$  Jy Hz. We estimate the ratio of delay spectra from data and simulations as  $\rho = |V_{b\tau}^D(\mathbf{b}, \tau)| / |V_{b\tau}^S(\mathbf{b}, \tau)|$ , where superscripts D and S denote data and simulation, respectively.

The median absolute deviation of  $\log_{10} \rho$  inside the *foreground wedge* for both pointings is  $\approx 0.28$ . This corresponds to  $\sim 90\%$  fractional difference between data and modeling on average with either pointing. We also simulated delay spectra after assigning spectral indices drawn randomly from a *gaussian* distribution with a mean of  $\langle\alpha_{\text{sp}}\rangle = -0.83$  and a HWHM of  $\Delta\alpha_{\text{sp}} = 0.35$  to the point sources in our compact foreground model. These simulations typically yielded a median absolute deviation



of  $\approx 0.29$  for  $\log_{10} \rho$  indicating fractional differences of  $\sim 95\%$ . This demonstrates that a fractional deviation of  $\sim 90\%$  observed between data and simulations is in line with expectations when the aforementioned uncertainty in foreground models, thermal noise fluctuations in measurements, and uncertainties in antenna power pattern due to random delay fluctuations are taken into account. Currently, we are significantly limited by the unavailability of all-sky foreground models at the observing frequency of 185 MHz.

These uncertainties are presented only to confirm the qualitative agreement already seen between Figures 3 and 7. These estimates are conservative. A full treatment of all uncertainties and deviations from ideal behavior such as frequency dependent errors in tile power-pattern (Bernardi et al. 2014), calibration (Datta et al. 2010), data corruption due to interference, anisoplanatic wide-field imaging and ionospheric effects (Intema et al. 2009) will bring the simulations much closer in agreement with observations, but is beyond the scope of this paper. **Hereafter**, our primary objective is to explore in detail the foreground signatures embedded in the *foreground wedge*.

## 5. RESULTS

Having shown that the simulation matches the data to the level of expected uncertainties, we proceed to examine in further detail the key signatures seen in simulated delay spectra. A number of factors are responsible for the characteristics noted in the delay spectra obtained from data and through simulations. We address these factors below:

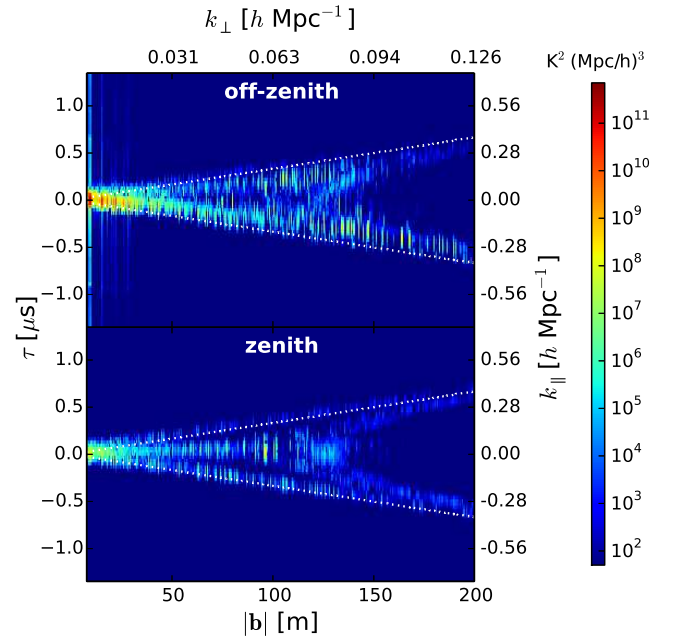
- **Sky Model:** Our model of the sky consists of compact and diffuse emission on diverse spatial scales as shown in Figures 5 and 6. It also consists of localized regions of strong emission such as the Galactic plane and Galactic center. In fact, the patch of sky for MWA observations is chosen from regions of low foreground emission. We will investigate the signatures of each component and their potential impact on *EoR window* contamination.
- **Baseline Orientation:** Since the spatial structure of our foreground model is not expected to be isotropic, we divide our antenna spacings by their orientation,  $\theta_b$ . We use the **four following bins sweeping  $45^\circ$  each:**  $-67.5^\circ \leq \theta_b < -22.5^\circ$ ,  $-22.5^\circ \leq \theta_b < 22.5^\circ$ ,  $22.5^\circ \leq \theta_b < 67.5^\circ$ , and  $67.5^\circ \leq \theta_b < 112.5^\circ$ . The bin centers are oriented towards South-East, East, North-East, and North respectively. **While the bin boundaries are arbitrary, they were so chosen to allow bin centers to be aligned along the cardinal and ordinal directions in one half-plane.** Since delays depend on  $\theta_b$ , binning by  $\theta_b$  allows us to match delay spectrum features to different sky directions.
- **Tile Pointing and Power-Pattern:** Since the MWA tiles are steered electronically, the power-pattern of the tile changes in any observing mode that tracks the **pointing center**. In our study, we take into account the effect of the changing tile power-pattern on the delay spectrum (Figure 4). The

LST of our data ranges from  $\sim 21$  hours through  $\sim 2$  hours, and for our analysis we chose the *off-zenith* and *zenith* pointings shown in Figure 2. We will show the secondary lobe structures in the tile power-pattern are tied to the foreground signatures in Fourier space.

In subsequent sections, we provide a detailed explanation of our results as a combination of factors noted above. Note that numerous features may overlap at different degrees of significance depending on combinations of parameters. We assign the features to their predominant causes. Secondly, we have used noiseless cases to clearly illustrate the observed foreground signatures. With the addition of noise in the visibilities, some of the weaker features may not be as prominently visible. Since the foreground signatures are far too numerous and they reside in a vast volume of parameter space such as antenna spacing length and orientation, power-pattern, patch of sky under observation, and instrumental configuration, we highlight only some examples of the most notable features observed in the delay spectra of foreground emission.

### 5.1. Diffuse Foreground Signatures

Figure 8 shows the amplitude of delay spectrum,  $|V_{b\tau}|$ , simulated with only the diffuse foreground model. The top and bottom panels correspond to *off-zenith* and *zenith* pointings, respectively.



**Figure 8.** Simulated delay spectrum power (in units of  $K^2 \text{ (Mpc/h)}^3$ ) for *off-zenith* (top) and *zenith* (bottom) pointings for the diffuse foreground model without any thermal noise. White lines mark the boundaries of the *foreground wedge* determined by the horizon delay limit and antenna spacing. The axes and color scale are identical to those in Figures 3 and 7. In the *zenith* pointing, delay spectrum from diffuse emission has a *two-pronged fork-shaped* structure and is present even at wide antenna spacings.

Here we examine in detail some examples of interesting features observed with the diffuse foreground model.

### 5.1.1. Galactic Center on Eastward Antenna Spacings

The most prominent signature seen in the *off-zenith* pointing (top panel of Figure 8) is due to the bright Galactic center situated on the western horizon co-located with one of the bright secondary lobes of the power-pattern. It appears as a bright branch in the delay spectrum near the negative delay horizon delay limit. This feature is strongest at short antenna spacings and fades with increasing antenna spacing. The bright signature is absent in the *zenith* pointing (bottom panel, Figure 8) because the Galactic center is below the horizon.

### 5.1.2. Diffuse Emission Delay Spectra

Figure 8 also demonstrates diffuse emission from within the primary field of view manifests in the *off-zenith* pointing as a branch at the top of the wedge, and at zero delay in the *zenith* pointing. The former is seen at positive delays because the primary lobe of the power-pattern is centered eastward of zenith, whereas in the latter it is centered at zenith. As we see from Equation 1, each baseline measures a single spatial mode on the sky with an angular size scale inversely proportional to the length of the baseline projected in the direction of the emission. Thus, in the *zenith* pointing, the signature of the smooth sky model, the horizontal line at zero delay, fades away on antenna spacings  $|b| \gtrsim 125$  m because the sky model is devoid of spatial structures on scales  $\lesssim 0.75^\circ$ . In the *off-zenith* pointing, we see power out to much longer baselines which is described below.

### 5.1.3. Diffuse Emission on Wide Antenna Spacings

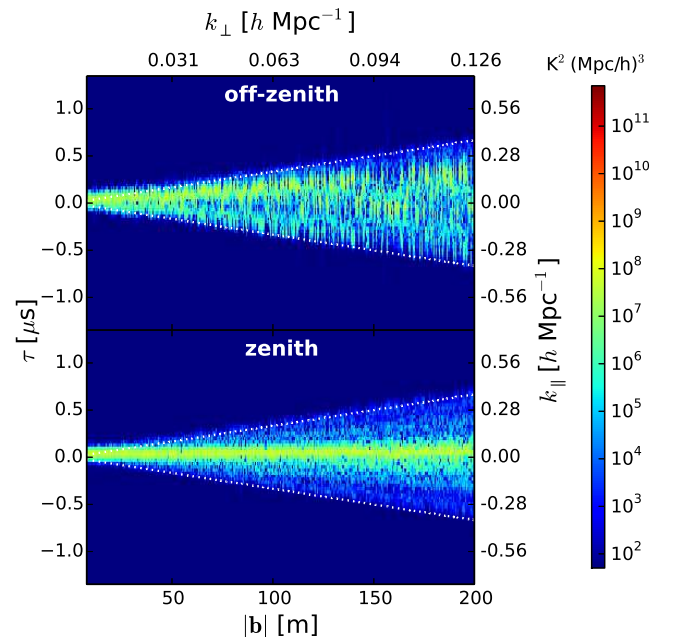
A very interesting signature of diffuse emission is revealed at regions near the positive horizon delay limit in the *off-zenith* pointing and at both positive and negative horizon delay limits in the *zenith* pointing even on wide antenna spacings ( $125 \text{ m} \lesssim |b| \leq 200 \text{ m}$ ). This is contrary to expectations because these longer baselines are not expected to be sensitive to diffuse emission (on scales  $\gtrsim 0.85^\circ$ ) of our input foreground model. **In wide-field observations**, long baselines appear shortened due to projection effects for off-axis emission, especially towards the horizon. **Consequently, they become sensitive to diffuse emission.** This effect is evident at all LSTs in our simulations and it naturally holds for short baselines, as well. Thus, diffuse emission from far off-axis directions manifests as an edge-heavy *two-pronged fork* across all baselines. It decreases in strength with increasing baseline length as expected but is present in all baseline orientations.

Interestingly, Thyagarajan et al. (2013) and Poher et al. (2013) have found a similar feature in their simulations and data respectively. In the latter, this feature is described as “edge brightening” and attributed to the Galactic plane near the horizon. From their discussion, it is unclear what fraction of power in that feature arises from ubiquitous diffuse emission unlike in our *zenith* pointing where the Galactic plane is not expected to play a significant role. On the other hand, Thyagarajan et al. (2013) statistically modeled point sources below the confusion limit and attributed the feature to an increase in solid angles sub-

tended by delay bins closer to the horizon limits thereby, enhancing the resulting integrated emission. This must be true for diffuse emission as well. Thus we argue the feature arises primarily due to an increase in sensitivity of long baselines to diffuse emission caused by foreshortening towards angles far off-axis, where the increased size scales (or solid angles) containing higher levels of integrated emission and spatial scales given by the inverse of foreshortened baseline vectors become matched.

### 5.2. Compact Foreground Signatures

Figure 9 shows the delay spectrum of the compact foreground sky model (see Figure 6) for *off-zenith* and *zenith* pointings in the top and bottom panels, respectively. In contrast to the delay spectrum of diffuse emission, compact emission manifests as a center-heavy structure in the delay spectrum with either pointing.



**Figure 9.** Same as Figure 8 but for a foreground model consisting of compact emission. Compact emission gives rise to centrally concentrated features and stays flat across antenna spacings in the foreground wedge.

The amplitude response of an interferometer to a point source is, to first order, flat with respect to baseline length. Since the main lobe of the power-pattern in the *off-zenith* pointing is centered eastward of zenith, the bulk of the compact foreground emission is seen in a branch with positive delay corresponding to the position of the primary lobe of the power-pattern. In the *zenith* pointing, compact emission from the same patch of sky is seen as a bright horizontal arm at zero delay since the primary lobe of the power-pattern is centered at zenith.

Foreground emission in zero delay and negative delay regions in the *off-zenith* pointing is caused by point sources co-located with secondary lobes of the power-pattern. On the other hand, point sources co-located with secondary lobes of power-pattern in the *zenith* pointing are revealed as faint but distinct branches at

positive and negative delays depending on the orientation of antenna spacing and direction of emission on the sky.

### 5.3. The “Pitchfork”

Delay spectra from the foreground model in our study display a composite feature set drawn from the features of compact and diffuse foreground models. Here we compare the relative strengths of emission from different spatial scales in our composite foreground model.

When not dominated by the bright emission from the Galactic center, which happens only for certain pointings at certain times, the delay spectrum of the combined foreground model is composed of diffuse and compact emission, in roughly equal measure. This is illustrated by a more detailed examination of the *zenith* pointing in our study.

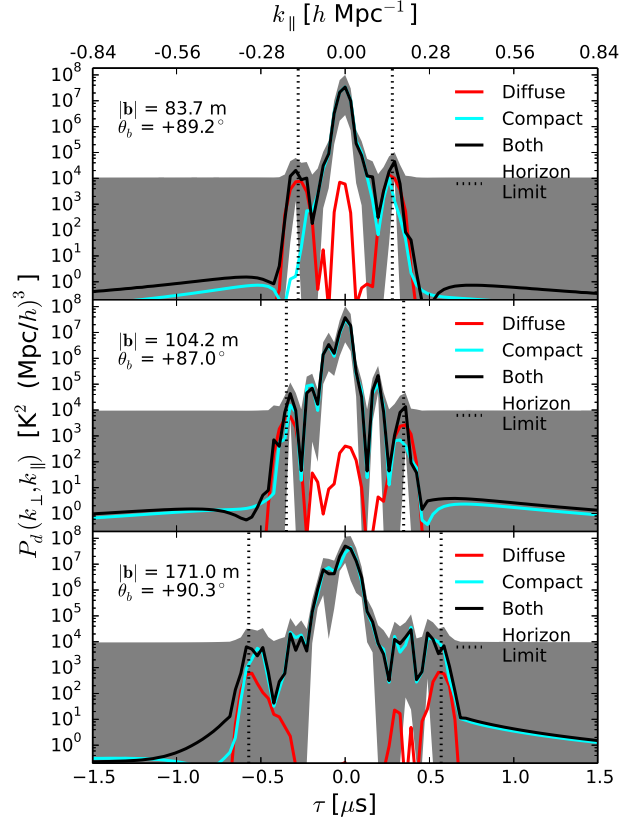
Figure 10 shows delay spectra of three antenna pairs of different antenna spacings oriented northward during the *zenith* pointing; each is a different vertical slice of the two dimensional delay spectrum plots shown in Figures 3, 7, 8, and 9. The diffuse, compact, and composite components are shown as solid red, cyan, and black lines, respectively. The horizon delay limits are shown as a pair of vertical dotted lines. The gray shaded area denotes the envelope of expected uncertainty in the delay spectrum. Uncertainty in emission in the *foreground wedge* (between the horizon delay limits) is dominated by the uncertainty in predicting the spectral index of compact foreground model, while thermal noise fluctuations dominate outside.

The zero-delay peak (corresponding to the main lobe in the power-pattern) with a value of  $\sim 10^8$ – $10^9$  Jy Hz, independent of antenna spacing, is predominantly determined by compact emission. The corresponding peak at zero-delay from diffuse foreground model is at least 10 times fainter and decreases drastically with an increase in antenna spacing. This is the response expected from different antenna spacings towards compact and diffuse emission.

Near the horizon delay limits at shorter antenna spacing, the diffuse component is brighter relative to the compact component. Here, diffuse emission does not decrease as rapidly with increasing antenna spacing as was seen at zero-delay. In fact, even on widely spaced antennas, diffuse emission in the delay spectrum near the horizon delay limits exceeds that in the main lobe by more than two orders of magnitude. We attribute this to apparent shortening of antenna spacings projected in the direction of diffuse emission entering far from the primary field of view, thereby giving rise to the edge-heavy *two-pronged fork* feature discussed in §5.1.3.

Simulations with the complete foreground model show the combination of center-heavy features on all antenna spacings from compact emission, and edge-heavy features from both compact and diffuse emission especially the latter even on wide antenna spacings. This results in a characteristic *pitchfork* structure imprinted in the *foreground wedge* and should be evident in observations.

All these observations are consistent with those from Figures 8 and 9. The observability of the *pitchfork* signature predicted in this paper depends on the relative levels of uncertainty in the foreground model and fluctuations from thermal noise. In our simulations, since



**Figure 10.** Simulated delay spectrum power for three chosen northward oriented antenna spacings of length:  $\sim 84$  m (*top*),  $\sim 104$  m (*middle*), and  $\sim 171$  m (*bottom*). The antenna spacing is specified in each panel along East, North and Upward directions. The solid red, cyan, and black lines denote contributions from diffuse, compact, and composite foreground models respectively. Vertical dotted lines mark the horizon delay limits. **Compact emission dominates the central regions of delay spectrum while both components, especially diffuse emission on short antenna spacings, dominate near the horizon delay limits, giving rise to a *pitchfork*-shaped structure.** The shaded region denotes the envelope of uncertainty around the composite model delay spectrum. This uncertainty is dictated by uncertainties in spectral indices of foreground models inside the delay horizon delay limits. Outside the horizon delay limits, it is predominantly due to thermal noise fluctuations.

thermal noise in these very short duration snapshots is  $\gtrsim 10^7$  Jy Hz, and features near the horizon delay limits are  $\sim 10^7$  Jy Hz, the *pitchfork* feature is not expected to be detected in a noisy scenario although this feature is marginally visible in the *zenith* pointing of observed data (see Figure 3). We attribute this to differences between our foreground model and the actual sky. Deeper observations should reveal the feature clearly.

We also note that increasing the antenna spacing results in progressively improving the resolution along the delay axis by increasing the number of delay bins inside the *foreground wedge*. This improves the localization of foreground objects whose signatures are imprinted in the delay spectrum. For instance, there is an increase in the number of secondary peaks in the delay spectrum between zero-delay and horizon delay limits as the antenna spacing increases from  $\sim 84$  m to  $\sim 171$  m. In this case, these correspond to secondary lobes of the power-pattern

that lie between the primary lobe and the horizon along the local meridian. At short antenna spacings, due to relatively lower resolution along the delay axis inside the *foreground wedge* and a consequent loss of localization of foreground emission, these secondary peaks blend in with other major peaks and are not distinctly visible. These findings are consistent with the discussion in §5.2.

In summary, the brightest signature ( $\gtrsim 10^{10}$  Jy Hz) is that of the Galactic center in the *off-zenith* pointing co-located at a westward secondary lobe with a significantly high gain. The next brightest signature ( $\sim 10^8$ – $10^9$  Jy Hz) is caused by compact emission appearing to be concentrated in the inner regions of the *foreground wedge* (near zero delays) rather than towards the boundaries. Diffuse emission co-located at the primary lobe of the power-pattern is fainter by approximately an order of magnitude relative to compact emission from the same region for a  $\sim 84$  m antenna spacing. But unlike the latter, diffuse emission decreases rapidly by over two orders of magnitude as the antenna spacing is widened to  $\sim 171$  m. However, diffuse emission is significantly higher near horizon delay limits compared to that in the primary lobe of the power-pattern as the antenna spacing is increased. This leads to edge-heavy features in the delay spectrum. Complemented by the center-heavy compact foreground features, we predict the presence of a *three-pronged pitchfork*-shaped signature in the delay spectrum of the foreground sky. We identify evidence for presence of this signature in actual MWA data, although deeper observations are needed to more clearly reveal the effect.

## 6. APPLICATIONS

Here, we will investigate the susceptibility of particular antenna spacings to foreground contamination arising out of bright foreground objects located near the horizon and present a technique to substantially mitigate such contamination.

The Galactic center in the *off-zenith* pointing is one such example already available in our study. Figure 11a shows the sky model (*top*: compact component, *bottom*: diffuse component) in this pointing. The Galactic center is the most dominant source of foreground contamination from the diffuse sky model and is co-located with a bright secondary lobe of the power pattern near the western horizon. Figure 11b shows the sky mapped to delays registered by the baseline vectors, of length 100 m for instance, oriented northward (top panel) and eastward (bottom panel). Since the Galactic center is located in the western sky, this figure demonstrates that it is observed at negative delay on a baseline vector oriented eastward and at zero delay on a baseline vector oriented northward. Figure 11c shows the delay spectra on baselines oriented northward ( $67.5^\circ \leq \theta_b < 112.5^\circ$ ) at the top and eastward ( $-22.5^\circ \leq \theta_b < 22.5^\circ$ ) at the bottom. The Galactic center manifests itself most distinctly near the negative horizon delay limit on short eastward baselines in the delay spectrum (bottom panel of Figure 11c). Consequently, the spillover caused by the instrument's spectral transfer function from the *foreground wedge* into the *EoR window* affects the northward baselines the least and is most severe in eastward baselines (particularly the short ones) evident by the bright vertical stripes of foreground contamination.

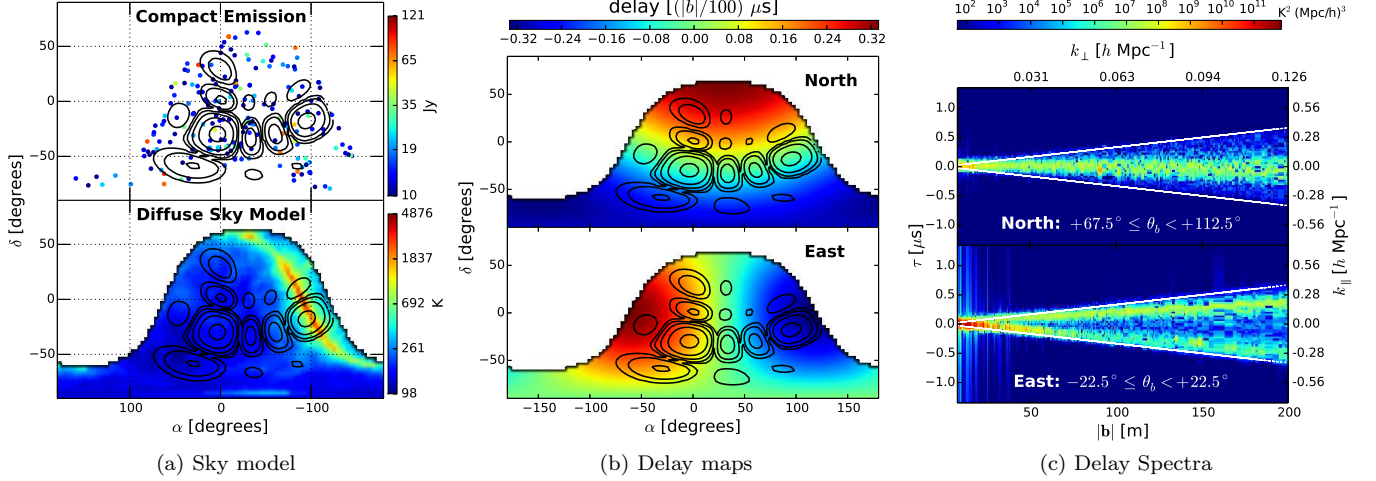
The delay spectrum,  $V_{b\tau}$ , not only carries information on spatial scales of foreground emission but also offers the unique advantage of viewing the sky through a combination of antenna spacing vectors and the delay axis. With a foreground model known *a priori* in which structures and locations of very bright foreground objects such as the Galactic center or AGN are available, we can predict their response across antenna spacings as a function of observing parameters such as LST, power-pattern, etc. This allows us to programmatically screen data for antenna spacings that are severely contaminated by foregrounds near the horizon delay limits in the delay spectrum. These can be weighted appropriately during data analysis. We demonstrate such a screening technique, whereby we use the bright object's location and structure to discard antenna spacings of certain lengths and orientations to mitigate foreground contamination in the *EoR window*.

In our example, we discard eastward antenna spacings ( $-22.5^\circ \leq \theta_b < 22.5^\circ$ ) of lengths  $|\mathbf{b}| < 30$  m. **This was determined as the limit beyond which foreground contamination levels are insensitive to any further removal of wider antenna spacings.** Figure 12 shows the delay spectra obtained with all antenna spacings (top panel) and after applying our screening technique (bottom panel) on the *off-zenith* observation. Notice the remarkable reduction in foreground spillover into the *EoR window* via the removal of bright vertical stripes on short eastward antenna spacings. The color scale range has been adjusted relative to the previous figures to show this significant reduction in foreground contamination.

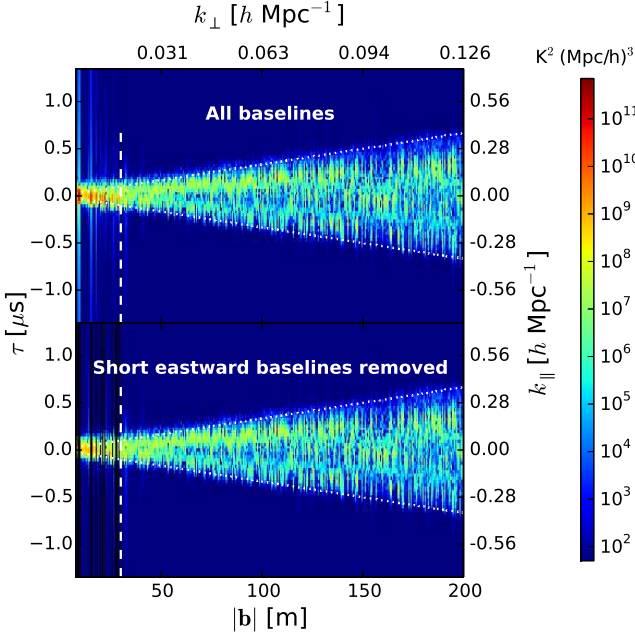
This screening technique can be generalized to optimize between foreground mitigation and loss of sensitivity from discarding data. Figure 13 shows how the typical foreground contamination<sup>24</sup> in the *EoR window* depends on the orientations and lengths of discarded antenna spacings. We choose antenna spacings oriented eastward to varying degrees of directedness, i.e.,  $-7.5^\circ \leq \theta_b < 7.5^\circ$  (solid circles),  $-15^\circ \leq \theta_b < 15^\circ$  (solid squares), and  $-22.5^\circ \leq \theta_b < 22.5^\circ$  (solid stars). Among antenna spacings that satisfy these criteria, we discard data from those whose lengths are shorter than  $|\mathbf{b}|_{\max}$  ( $x$ -axis) and show foreground contamination estimated in the *EoR window* from all remaining antenna spacings. In other words, these plots demonstrate the progress in mitigation as orientation and maximum length of discarded antenna spacings are varied. The fraction of discarded antenna spacings discarded relative to the total number is shown in dotted lines for different ranges of  $\theta_b$ . It is seen that foreground contamination can be mitigated by a factor between  $\sim 1.5$  ( $|\theta_b| \leq 7.5^\circ$ ) and  $\sim 10$  ( $|\theta_b| \leq 22.5^\circ$ ). The latter limit is achieved with a mere 5% loss of data for  $|\mathbf{b}|_{\max} \simeq 30$  m. And discarding antenna spacings with lengths  $|\mathbf{b}| \gtrsim 30$  m does not mitigate foreground contamination any further and would only lead to loss of sensitivity as the fraction of discarded baselines increases from  $\sim 5\%$  to  $\sim 25\%$ . On the other hand, a bright point source at the same location will give rise to foreground contamination even on longer antenna spacings. Such cases will necessitate discarding more or,

<sup>24</sup> Foreground contamination is measured by standard deviation of noiseless  $P_d(\mathbf{k}_\perp, k_\parallel)$  from foregrounds in the *EoR window*.



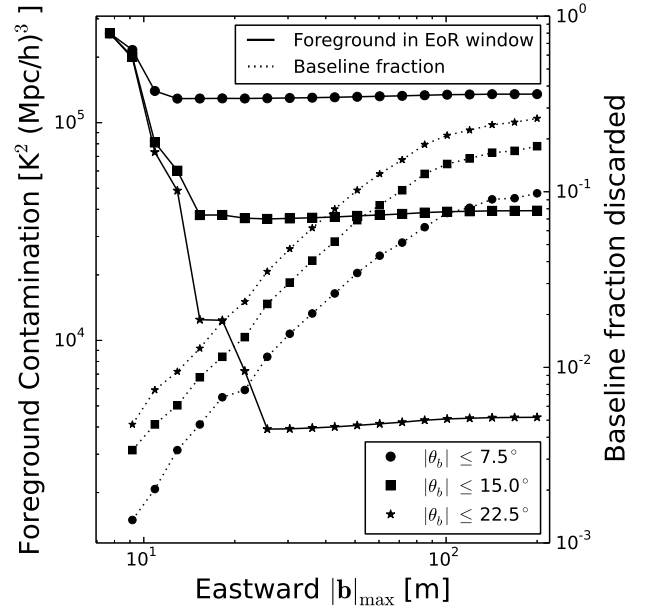


**Figure 11.** (a): Sky model showing compact (*top*) and diffuse (*bottom*) emission. Contours of power pattern are overlaid whose levels are identical to those in Figures 5 and 6. The Galactic center is very prominent in diffuse emission in the western sky and is co-located with a bright secondary lobe of the power pattern. (b): Sky hemisphere mapped to delays observed on antenna spacings with northward (*top*) and eastward (*bottom*) orientations. Color scale shown is for a 100 m antenna spacing. Delays vary linearly with antenna spacing length. The bright Galactic center in the western sky is recorded at zero delays in northward antenna spacings and close to negative horizon delay limit on eastward antenna spacings. (c): Simulated delay spectra **power** on antenna spacings oriented northward (*top*) and eastward (*bottom*). White lines denote horizon delay limits. The bright Galactic center is prominently visible close to negative horizon delay limit, especially on short eastward antenna spacings. These are also the most severely contaminated by foreground spillover. The northward antenna spacings, on the other hand, are the least contaminated.



**Figure 12.** Simulated delay spectra **power** for the *off-zenith* pointing with all antenna spacings included (*top*) and with short eastward antenna spacings discarded (*bottom*). Discarded antenna spacings (black vertical stripes) have lengths  $|b| < 30$  m (leftward of vertical dashed line) and orientations  $|\theta_b| < 22.5^\circ$ . The spillover from the bright Galactic center near the negative horizon delay limit from the *foreground wedge* prominent when all antenna spacings are used is lowered by **nearly two orders** of magnitude when short eastward antenna spacings are discarded. Color scale has been adjusted to emphasize mitigation achieved in foreground contamination.

in the worst case, all of the eastward oriented antenna spacings. **These results are specific to the MWA data. In general, the array configuration will be a significant factor in determining such thresholds.**



**Figure 13.** Drop in foreground contamination in the *EoR window*, and loss of data for the *off-zenith* pointing as a function of discarded baselines. Eastward baselines with varying degrees of directedness –  $|\theta_b| < 7.5^\circ$  (solid circles),  $|\theta_b| < 15^\circ$  (solid squares), and  $|\theta_b| < 22.5^\circ$  (solid stars) – and lengths  $|b| \leq |b|_{\text{max}}$  (x-axis) are discarded. Loss of data (dotted lines) is measured by discarded baselines as a fraction of the total number for the corresponding cases. Foreground contamination in the *EoR window* (solid lines) drops by a factor  $\sim 2$  ( $|\theta_b| \leq 7.5^\circ$ ) to  $\sim 100$  ( $|\theta_b| \leq 22.5^\circ$ ). The latter limit can be achieved with a mere 5% loss of data at  $|b|_{\text{max}} \simeq 30$  m, and discarding longer baselines ( $|b| \gtrsim 30$  m) has no effect in further reducing foreground contamination.

In principle, instead of discarding selected antenna spacings altogether, we could down-weight them based on an optimal scheme. For instance, the estimates of co-



variance computed from the delay transform bins can be naturally fed into the covariance-weighted power spectrum estimation techniques (Liu et al. 2014a,b). It could also be used to downweight or flag contaminated baselines in imaging applications. This technique provides a very simple and yet effective tool in adding a layer of control to mitigate effects of foreground contamination in EoR data analysis.

## 7. ROLE OF ANTENNA GEOMETRY

Having examined the role the foregrounds play in determining the delay spectrum obtained with an interferometer array, we turn our attention to another crucial factor, namely, the power pattern of the antenna (refer to equations 1 and 2). In the following discussion, we assume there are no random delay fluctuations in the MWA tile beamforming process. The model power pattern so obtained is different from the one we used earlier, but for the present discussion it still serves as a good reference (Figure 4). Since the previous model suffices, we do not plot the new power pattern model obtained with ideal beamforming. We also assume an ideal flat bandpass shape over the 30.72 MHz bandwidth unlike the flagging of the edges of the coarse sub-bands described earlier in this paper, while still applying a *Blackman-Harris* window function.

### 7.1. Uniformly Illuminated Sky

The brightness distribution on the sky was fixed to be a constant equal to the mean over the whole sky at 185 MHz with no variation along frequency. This helps isolate the signatures of the antenna power pattern from those of the foregrounds. Figure 14 shows the delay spectrum power of such a sky model with the model power pattern of an MWA tile.

Although not identical, these delay spectra power bear a close resemblance to those obtained with the diffuse sky model (see Figure 8). This indicates that the delay spectra power seen from diffuse foregrounds is primarily explained by the delay spectrum signatures of the underlying power pattern, with the additional variations coming from anisotropic deviations of the diffuse foreground model from a uniformly illuminated sky.

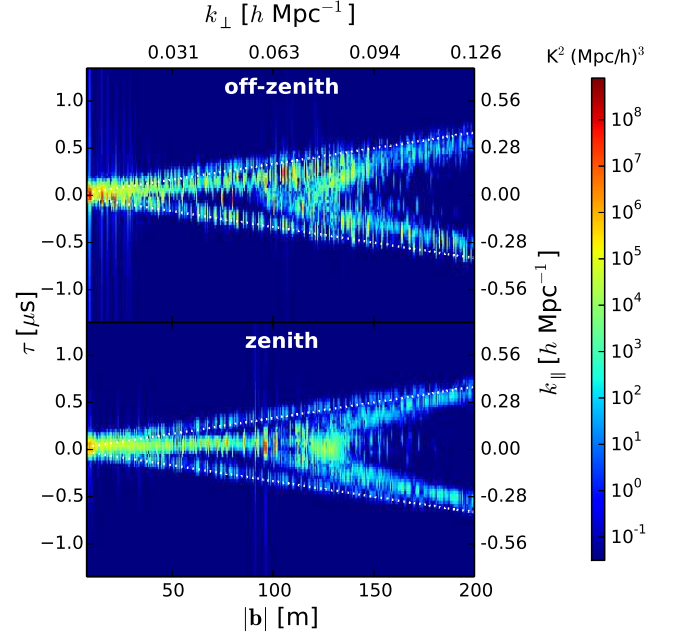
The edge-heavy *two-pronged* features are evident, which are very similar to those seen earlier in the case of diffuse emission. As reasoned in §5.1.3, the foreshortening of long baselines causes them to be sensitive to emission from near the horizon.

Branches of foreground power seen at positive delays and close to the negative horizon delay limit in the *off-zenith* pointing correspond to radiation received from the direction of the primary lobe and the far eastward side-lobe, respectively, in the power pattern. On the other hand, the symmetry of the delay spectrum around  $\tau = 0$  seen in the *zenith* pointing is as expected from a symmetric power pattern.

### 7.2. Experiments with Antenna Geometry

## 8. SUMMARY

Our primary motivation in this work is to understand how the various bright foregrounds will manifest in three dimensional power spectrum of HI from 21 cm reionization observations. When the signal is expressed in



**Figure 14.** Similar to Figure 8 but for a uniform sky brightness model. The features bear a close resemblance to those obtained with the diffuse emission model. The edge-heavy *two-pronged* features arise from foreshortening of baselines which increases their sensitivity to emission from larger size scales from near the horizon. The symmetries around  $\tau = 0$  or lack thereof correspond to symmetries in the power patterns of the respective pointings (see Figure 4).

units of temperature variance, the dynamic range between bright foregrounds and the 21 cm signal is expected to be  $\sim 10^8$ ; a detailed understanding of how foregrounds can corrupt the 21 cm power spectrum is therefore essential. This analysis extends previous work by simulating the entire sky rather than just the central field of view and by providing a comparison with early observations from the MWA. By making use of the delay spectrum technique to estimate the power spectrum, we are able to observe the effects of foregrounds while avoiding entanglements with more complex power spectrum estimators.

Simulating in many important respects the response of the MWA to an all-sky foreground model that consists of diffuse Galactic emission from de Oliveira-Costa et al. (2008) and bright point sources from the NVSS and SUMSS catalogs, we confirm that the modeled delay spectra are in agreement with data obtained with the MWA, to the extent allowed by levels of uncertainty known in the foreground models and thermal noise fluctuations in measurements.

Our simulations enable us to identify numerous signatures of different components of foreground emission seen in the delay spectra. We establish the relationship between these signatures and observing parameters such as antenna pointing and LST, instrument parameters such as antenna power-pattern, and foreground parameters such as the nature of emission, spectral index, etc.

The bright Galactic center at the edge of the western horizon co-located with one of the far secondary lobes of MWA tile power-pattern is the brightest source of foreground contamination in the *off-zenith* pointing. It manifests itself near the negative horizon delay limit in the

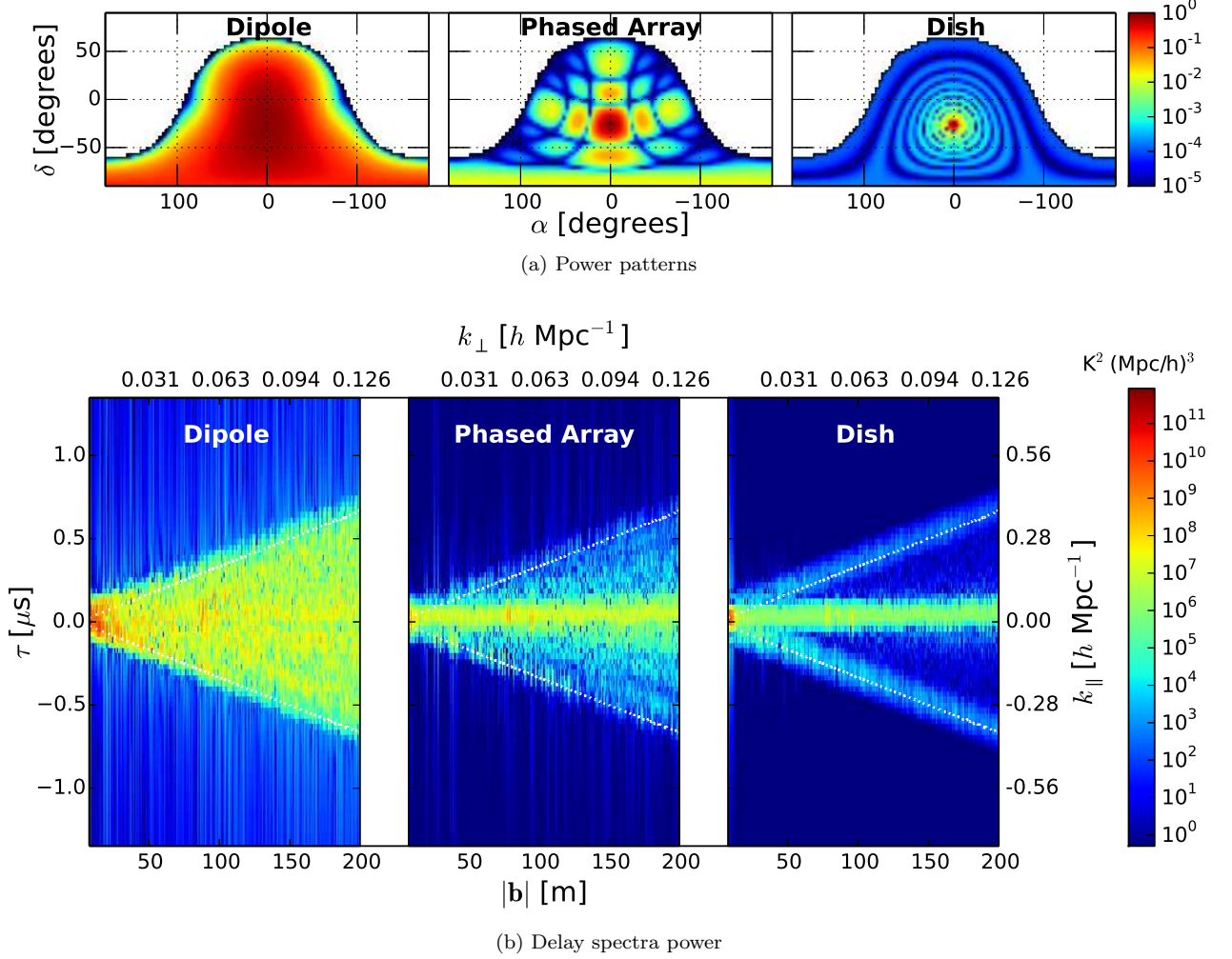


Figure 15.

delay spectrum on antenna spacings oriented eastward.

As expected, diffuse emission in the primary beam of the antenna power-pattern is prominent on shorter antenna spacings. However, the most interesting result is its footprint on wide antenna spacings near the horizon delay limits, an edge-heavy *two-pronged fork*-shaped signature. This is due to apparent shortening of wide antenna spacings in the direction of foreground emission far off-axis, thereby retaining their response to extended emission. On the other hand, compact emission predominantly maps onto central regions of the *foreground wedge*. Features arising from compact emission co-located with primary and secondary lobes of the antenna power-pattern have been identified. In general, delay spectrum signatures of compact emission are center-heavy, in clear contrast to those from diffuse emission. A composite foreground model consisting of diffuse and compact foregrounds combines the characteristic individual shapes into a *pitchfork*-shaped structure in the *foreground wedge*. This will be distinctly visible when the thermal noise floor is sufficiently lowered, as longer observations are processed through the MWA analysis pipelines.

In conclusion, we find that inclusion of emission models, both diffuse and compact, all the way to the horizon is essential to explaining the observed power spectrum.

We also provide a simple and effective tool based on the delay spectrum technique **that can potentially** mitigate foreground contamination by an order of magnitude in EoR data analysis by discarding or down-weighting data from antenna pairs most affected by foreground contamination as a function of antenna spacing vector and time of observation, with negligible loss of sensitivity.

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## REFERENCES

- Ali, S. S., Bharadwaj, S., & Chengalur, J. N. 2008, *MNRAS*, 385, 2166
- Beardsley, A. P., Hazelton, B. J., Morales, M. F., et al. 2012, *MNRAS*, 425, 1781
- . 2013, *MNRAS*, 429, L5
- Bernardi, G., McQuinn, M., & Greenhill, L. J. 2014, *ArXiv e-prints*, arXiv:1404.0887
- Bernardi, G., de Bruyn, A. G., Brentjens, M. A., et al. 2009, *A&A*, 500, 965
- Bernardi, G., de Bruyn, A. G., Harker, G., et al. 2010, *A&A*, 522, A67
- Bock, D. C.-J., Large, M. I., & Sadler, E. M. 1999, *AJ*, 117, 1578
- Bowman, J. D., Morales, M. F., & Hewitt, J. N. 2006, *ApJ*, 638, 20
- . 2009, *ApJ*, 695, 183
- Bowman, J. D., Barnes, D. G., Briggs, F. H., et al. 2007, *AJ*, 133, 1505
- Bowman, J. D., Cairns, I., Kaplan, D. L., et al. 2013, *PASA*, 30, 31
- Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, *AJ*, 115, 1693
- Datta, A., Bowman, J. D., & Carilli, C. L. 2010, *ApJ*, 724, 526
- de Oliveira-Costa, A., Tegmark, M., Gaensler, B. M., et al. 2008, *MNRAS*, 388, 247
- Di Matteo, T., Perna, R., Abel, T., & Rees, M. J. 2002, *ApJ*, 564, 576
- Dillon, J. S., Liu, A., & Tegmark, M. 2013, *Phys. Rev. D*, 87, 043005
- Dillon, J. S., Liu, A., Williams, C. L., et al. 2014, *Phys. Rev. D*, 89, 023002
- Furlanetto, S. R., Oh, S. P., & Briggs, F. H. 2006, *Phys. Rep.*, 433, 181
- Ghosh, A., Prasad, J., Bharadwaj, S., Ali, S. S., & Chengalur, J. N. 2012, *MNRAS*, 426, 3295
- Haslam, C. G. T., Salter, C. J., Stoffel, H., & Wilson, W. E. 1982, *A&AS*, 47, 1
- Hazelton, B. J., Morales, M. F., & Sullivan, I. S. 2013, *ApJ*, 770, 156
- Hurley-Walker, N., Morgan, J., Wayth, R. B., et al. 2014, *ArXiv e-prints*, arXiv:1410.0790
- Iliev, I. T., Shapiro, P. R., Ferrara, A., & Martel, H. 2002, *ApJ*, 572, L123
- Intema, H. T., van der Tol, S., Cotton, W. D., et al. 2009, *A&A*, 501, 1185
- Liu, A., Parsons, A. R., & Trott, C. M. 2014a, *Phys. Rev. D*, 90, 023018
- . 2014b, *Phys. Rev. D*, 90, 023019
- Liu, A., & Tegmark, M. 2011, *Phys. Rev. D*, 83, 103006
- Liu, A., Tegmark, M., Bowman, J., Hewitt, J., & Zaldarriaga, M. 2009, *MNRAS*, 398, 401
- Lonsdale, C. J., Cappallo, R. J., Morales, M. F., et al. 2009, *IEEE Proceedings*, 97, 1497
- Madau, P., Meiksin, A., & Rees, M. J. 1997, *ApJ*, 475, 429
- Mauch, T., Murphy, T., Buttery, H. J., et al. 2003, *MNRAS*, 342, 1117
- McQuinn, M., Zahn, O., Zaldarriaga, M., Hernquist, L., & Furlanetto, S. R. 2006, *ApJ*, 653, 815
- Morales, M. F., Bowman, J. D., & Hewitt, J. N. 2006, *ApJ*, 648, 767
- Morales, M. F., Hazelton, B., Sullivan, I., & Beardsley, A. 2012, *ApJ*, 752, 137
- Morales, M. F., & Hewitt, J. 2004, *ApJ*, 615, 7
- Offringa, A. R., de Bruyn, A. G., Biehl, M., et al. 2010, *MNRAS*, 405, 155
- Offringa, A. R., van de Gronde, J. J., & Roerdink, J. B. T. M. 2012, *A&A*, 539, A95
- Parsons, A., Pober, J., McQuinn, M., Jacobs, D., & Aguirre, J. 2012a, *ApJ*, 753, 81
- Parsons, A. R., & Backer, D. C. 2009, *AJ*, 138, 219
- Parsons, A. R., Pober, J. C., Aguirre, J. E., et al. 2012b, *ApJ*, 756, 165
- Parsons, A. R., Backer, D. C., Foster, G. S., et al. 2010, *AJ*, 139, 1468
- Pober, J. C., Parsons, A. R., Aguirre, J. E., et al. 2013, *ApJ*, 768, L36
- Pober, J. C., Liu, A., Dillon, J. S., et al. 2014, *ApJ*, 782, 66
- Salvini, S., & Wijnholds, S. J. 2014, *ArXiv e-prints*, arXiv:1410.2101
- Scott, D., & Rees, M. J. 1990, *MNRAS*, 247, 510
- Sullivan, I. S., Morales, M. F., Hazelton, B. J., et al. 2012, *ApJ*, 759, 17
- Sunyaev, R. A., & Zeldovich, Y. B. 1972, *A&A*, 20, 189
- Sutinjo, A., O’Sullivan, J., Lenc, E., et al. 2014, *ArXiv e-prints*, arXiv:1412.4466
- Taylor, G. B., Carilli, C. L., & Perley, R. A., eds. 1999, *Astronomical Society of the Pacific Conference Series*, Vol. 180, *Synthesis Imaging in Radio Astronomy II*
- Thompson, A. R., Moran, J. M., & Swenson, Jr., G. W. 2001, *Interferometry and Synthesis in Radio Astronomy*, 2nd Edition (Wiley)
- Thyagarajan, N., Udaya Shankar, N., Subrahmanyan, R., et al. 2013, *ApJ*, 776, 6
- Tingay, S. J., Goeke, R., Bowman, J. D., et al. 2013, *PASA*, 30, 7
- Tozzi, P., Madau, P., Meiksin, A., & Rees, M. J. 2000, *ApJ*, 528, 597
- Trott, C. M., Wayth, R. B., & Tingay, S. J. 2012, *ApJ*, 757, 101
- van Cittert, P. H. 1934, *Physica*, 1, 201
- van Haarlem, M. P., Wise, M. W., Gunst, A. W., et al. 2013, *A&A*, 556, A2
- Vedantham, H., Udaya Shankar, N., & Subrahmanyan, R. 2012, *ApJ*, 745, 176
- Zaldarriaga, M., Furlanetto, S. R., & Hernquist, L. 2004, *ApJ*, 608, 622
- Zernike, F. 1938, *Physica*, 5, 785